ROADPRINT: PRACTICAL PAVEMENT LIFE CYCLE ASSESSMENT (LCA) USING GENERALLY AVAILABLE DATA

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ABSTRACT

This paper describes the development of *Roadprint* (http://clients.paviasystems.com/wfl), an online pavement life cycle assessment (LCA) tool designed specifically to be used by pavement practitioners. This process highlights key issues confronting pavement LCA, and attempts to accommodate them yet still deliver a tool that produces results capable of being used for inventories and differentiating amongst different pavements. Findings include: 1) *Roadprint* is able to perform pavement LCA, 2) standard LCA issues limit the wide-scale use of pavement LCA, 3) pavement LCA will remain a research-level topic in the absence of Federal or State mandates, 4) useable pavement LCA tools require numerous simplifications of the LCA process, 5) most LCA impact categories are flawed or not understood, and 6) online delivery is mandatory to achieve broad reach. Recommendations from this research are 1) pavement LCA needs a standard method akin to that of life cycle cost analysis (LCCA), 2) the use phase (i.e., pavement's influence after initial construction) ought to be considered and done so separately analogous to how user costs are considered in LCCA, 3) any pavement LCA tool must clearly communicate some basic parameters such as data sources and quality, allocation, construction equipment and warm mix asphalt modeling methods, and feedstock inclusion/exclusion and value.

INTRODUCTION

Life cycle assessment (LCA) is a technique that can be used to quantify environmental impacts associated with a product, process or service. In the transportation sector LCA is promising because it can begin to quantify the impacts of infrastructure and operations on the environment, which can then assist in rational decision-making that includes the environment in a more quantitative manner. Although LCA has begun to be applied to pavement systems, the practice is in its infancy and, as yet, is rather ill-defined. Nonetheless, there are indicators that LCA applications to transportation infrastructure and operations will grow in the next decade as requirements to quantify environmental impacts grow and the ability to do so becomes more economical.

LCA can and has been applied to pavement systems for about 15 years now (taking *(1)* as the origin). Initial efforts were comprehensive and labor intensive *(e.g., 1)*, with more recent efforts taking advantage of several calculators developed for the specific purpose of pavement LCA *(e.g., 2,3,4,5)*. These recent efforts are trending towards making LCA possible for engineers involved in transportation construction and operations that have a need, but not the expertise, to use LCA.

To date, pavement LCA tool development has been limited by narrow data sets *(e.g., 3,4)*, high purchase prices *(e.g., 6)*, errors *(e.g., 5)*, complexity *(7)*, or a lack of access *(e.g., 8)*. Most importantly, the lack of a common standard beyond ISO 14040/14044 and the paucity of high-quality data effectively prevent comparison of LCA results from one tool or study with another. While all of these issues can be overcome, the necessary effort and funding to do so is not likely forthcoming in the near future if ever. This, however, may not be fatal. It is possible that LCA can be used to provide meaningful information given general data sets of marginal quality and be free of major errors, straightforward and quick to use, readily available, and free.

Scope

This paper describes the development, testing, and assessment of *Roadprint*, an online pavement LCA tool designed specifically to 1) be used by pavement practitioners, 2) be freely accessible on the Web, 3) use currently available general data, 4) be readily updated when new data are available, 5) be transparent about its data sources and quality, 6) able to differentiate between key paving practices. *Roadprint* was originally developed and tested in *Microsoft Excel* and then translated to an online platform. It currently resides at http://www.pavementinteractive.org/Roadprint and is free to use.

BACKGROUND

Pavement Life Cycle

It is useful to divide a pavement's life cycle into several significant phases in order to discuss LCA scopes. Note that most processes associated with pavement (e.g., construction, transportation, materials production) are interrelated and could reasonably be included in several different phases. Phases as defined by *(9)* are:

- **Materials production**. All those processes involved in pavement materials acquisition (e.g., mining, crude oil extraction) and processing (e.g., refining, manufacturing, mixing).
- **Pavement design**. The process of identifying the functional requirements of a pavement; gathering design information related to the subgrade, existing pavement structure (if present), climate, and traffic and then selecting and specifying materials and the pavement structural composition.
- **Construction**. All those processes and equipment associated with the construction of pavement systems. Generally, construction activities are associated with initial construction as well as subsequent maintenance and rehabilitation efforts.
- **Use**. Interactions of pavement with vehicle operations (e.g., roughness, deflection, and macro-texture) and the environment (e.g., stormwater disposition, heat capacity/conductivity, and reflectivity).

- **Maintenance and preservation**. Actions that help slow the rate of deterioration of a pavement by identifying and addressing specific pavement deficiencies that contribute to overall deterioration.
- **End-of-life**. Final disposition and subsequent reuse, processing, and/or recycling of any portion of a pavement system that has reached the end of its performance life.

Key Issues with Pavement LCA

Reap et al. *(10,11)* summarized key issues in LCA and their findings remain relevant today for many industry sectors including pavements. They found 15 major problem areas, of which some of the most vexing for pavement LCA are:

- **Boundary selection**. There is no standard for selecting the processes and activities that should be included in a LCA. Therefore, most pavement LCAs are not equivalent because they do not include the same items. Particularly problematic is the inclusion/exclusion of the use phase of the pavement life cycle.
- **Allocation**. "…appropriately allocating the environmental burdens of multifunctional processes amongst its functions or products" *(10)* is especially problematic for bitumen production and recycled materials use.
- **Impact category and methodology selection**. Impact categories are not consistent between LCA studies and many of those that are used are poorly understood, suffer from incomplete data, double-counting of LCIA results, or are poor representations of actual impacts.
- **Spatial variation and local environmental uniqueness.** Emissions occur at various locations and in multiple media (e.g., land, water, air). It is usually ignored that impacts can vary widely depending upon local sensitivities.
- **Uncertainty**. The reliability of a LCA depends upon its uncertainty. Most existing tools do not consider uncertainty. Therefore, their results can convey a false accuracy. There are also issues with uncertainty being the dominant characteristic of a LCA and thus preventing meaningful conclusions about the preference of one alternative over another.
- **Data availability and quality**. Much data involved in pavement LCA simply does not exist publically, has never been collected, or is of questionable quality due to its age, collection location, or measurement methods.

Finally, it may not be prudent to consider pavements in isolation. An LCA of just the pavement typically ignores the rest of the roadway and right-of-way, its function, and most sociological and economic impacts.

STATE OF THE PRACTICE

Pavement LCA can be useful for 1) inventorying key environmental outputs such as GHG emissions, 2) decision support, and 3) process improvement. The LCA functions of decision support and process improvement are only relevant if the owner-agency values LCA outputs in their decisions and processes. This usually occurs when such items are regulated or required to be inventoried for a higher authority (e.g., Federal government). Within the U.S. there are no specific Federal requirements to conduct LCA on pavements. It may be argued that several larger directives (National Environmental Policy Act, state GHG reduction mandates and reporting, cap-and-trade schemes, sustainability rating systems) could result in future requirements for public road owners to inventory GHG emissions from the infrastructure they put in place, which may ultimately result in the use of LCA on road projects. Non-traditional bid evaluation could also potentially include evaluation standards on energy and emissions associated with infrastructure.

Existing Tools

Efforts over the past 10 years have produced a number of LCA tools that are applicable to pavements. Amongst the more available ones are *PE-2 (3)*, *CHANGER (6)*, *EIO-LC*A *(12)*, *PaLATE (5)*, *GreenDOT (7)*, *BenReMod (2)*, and the *Athena Impact Estimator for Highways (4)*. These efforts represent significant progress in making LCA methods accessible and relevant to the pavement industry. However, like all LCAs they suffer from the key pavement LCA issues discussed previously.

METHOD

This section describes the method used to develop *Roadprint* in relation to the five LCA steps defined in *(13)*. It is meant to give insight into the design decisions made in light of the six development requirements listed earlier.

Five LCA Steps

<u>Goal</u>
The goal of *Roadprint* is to allow pavement practitioners to conduct a pavement LCA and obtain acceptable results using inputs typically available to them in a reasonable timeframe. Specific design goals were discussed in the "Scope" section of this paper. In general, the guiding principal in development was to simplify the process as much as possible while retaining the ability to differentiate between outputs from different states and those that include varying amounts of warm mix asphalt (WMA), reclaimed asphalt pavement (RAP), fly ash, and slag.

<u>Scope</u>
The functional unit is one lane-mile of pavement structure intended to serve a defined vehicle traffic for a set duration with a required service level. Pavement design is the recognized process that takes into account these features, and is what will determine the specific functional unit for any analysis. In addition to pavement design defining the functional unit, the *Roadprint* system boundary includes the following pavement life phases: materials production, construction, maintenance and preservation, and end-of-life phases (Figure 1). This leaves out the use phase, which some have argued to be the most influential of all *(e.g., 9)*. The use phase is planned as a future addition where it will be modeled separately akin to how user costs are treated in life cycle cost analysis (LCCA) *(14)*.

<u>Life Cycle Inventory Analysis (LCIA)</u>
Available data sources were reviewed and the following sources chosen for the *Roadprint* database:

- Energy/electricity generation: *(15)*
- Energy Mix: *(16)*
- Transportation: *(15)* as extracted by University of Washington Mechanical Engineering Department in 2008
- Construction Equipment: *(17)*
- Bitumen Production: *(18)*
- Cement Production: *(19)*
- Aggregate Production Energy: *(19)* and *(20)*

- Sand/gravel Production: Energy: *(19)* and *(20)*
- PCC Production: *(19)*
- HMA Production: *(1)* and *(21)*
- Steel Production: *(17)*

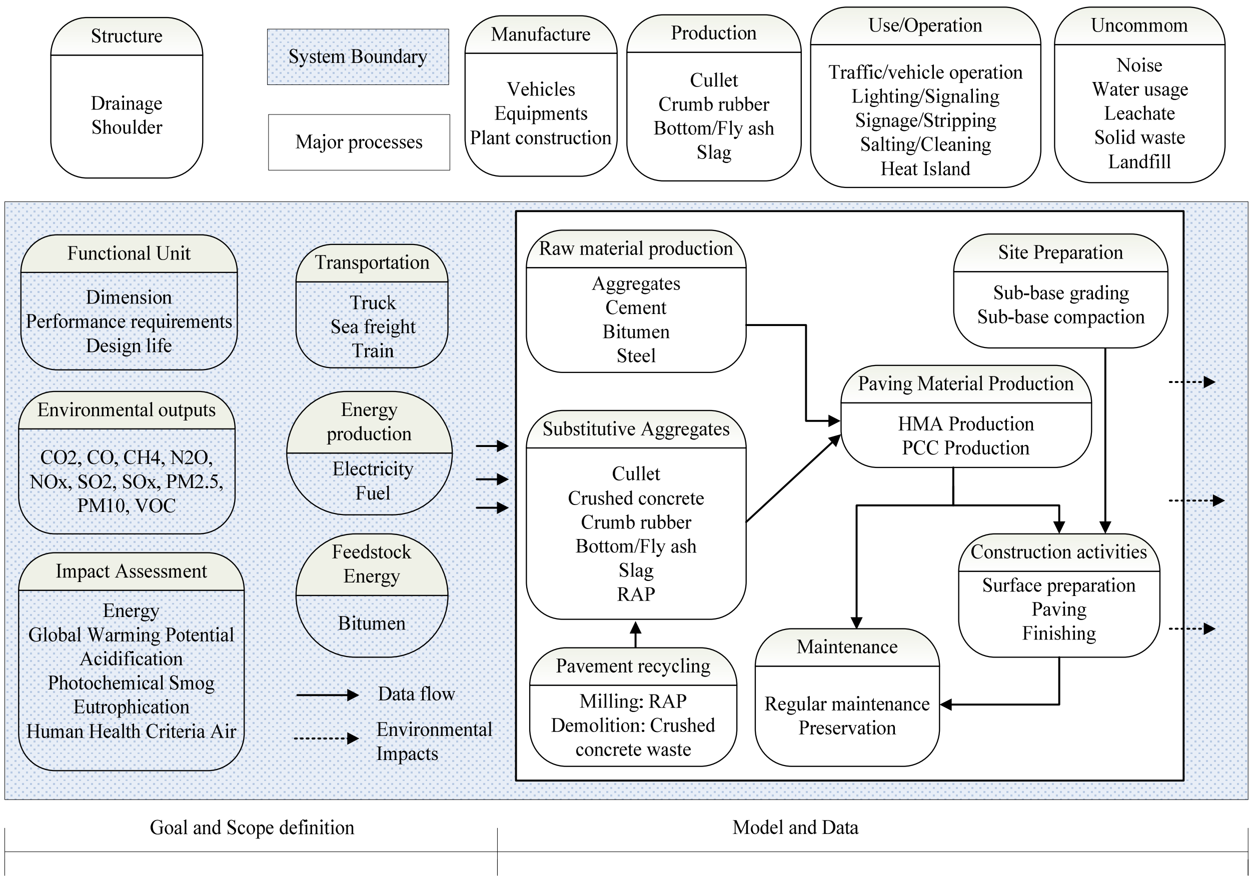

Figure 1: *Roadprint* system boundary.

Data Quality is Generally Low

This paper quantifies data quality using an A/B scoring system described by Cooper and Kahn *(22)*. This system lists the parameters that must be met for data to be considered A quality in each category, with data not meeting the requirements designated B quality. Of note, for pavement LCA most categories in every process are rated B (lower quality data, Table 1).

Recycled Materials Are Free Processes

Recycled materials (except cullet) are modeled as “free processes” meaning that there are no environmental outputs associated with the processing of these materials. This is done because 1) available data describing the recycling processes is somewhat incomplete, and 2) there is not yet published consensus on allocation issues associated with recycled materials. Once the necessary data are available, they can be readily incorporated into *Roadprint*’s data structure.

Table 1: *Roadprint* Data Quality Scoring (as described in *22*)

Category	Bitumen	Cement	Aggregate	HMA/WMA	PCC	Steel	Glass Cullet	Equipment	Transport	Energy
Reliability and reproducibility	A	A	A	B	B	B	B	B	B	B
Flow data completeness	B	B	B	B	B	A	B	A	A	A
Temporal coverage	B	B	B	B	B	B	B	B	B	B
Geographic coverage	B	A	A	A	A	A	B	A	A	A
Technological coverage	A	A	A	B	B	B	B	B	B	B
Uncertainty	B	B	B	B	B	B	B	B	B	B
Precision	B	B	B	B	B	B	B	B	B	B

WMA Modeling is Simplistic

WMA is modeled as a process that reduces energy use and emissions by a fixed, user-defined amount. LCIs for various WMA technologies are not currently available. Once available, they can be incorporated into *Roadprint*'s data structure.

Mixture Modeling is Different between HMA and PCC

Users can enter the exact proportions for HMA mixtures, but can only choose from seven pre-defined mixtures for PCC because of the way the PCC data source is reported *(19)*.

Construction Productivity is Modeled

Roadprint includes a simple productivity model for construction equipment and material transport to the construction site. Users can input key construction equipment parameters and *Roadprint* will calculate operation time, number of truck trips required, etc. which is then used to determine outputs for construction equipment.

Feedstock Energy is Included but Separately Identified

Feedstock energy is the energy contained in a material that is not used as an energy source in the product system *(9)*. ISO 14044 requires it to be included in the energy inventory. This is problematic in pavement LCA because bitumen stores a significant amount of energy; so much so that the inclusion or exclusion of feedstock energy can significantly alter results. For example, it can take 0.4 to 6 MJ/kg to produce bitumen *(23)*, but the stored energy in bitumen can be in the 35.5 to 41.2 MJ/kg range (95% confidence intervals reported by *24*). *Roadprint* allows the user to input feedstock energy (in MJ/kg) and then reports energy consumption both with and without feedstock energy.

Emissions Categories

Three categories are used to group emissions: materials production (all upstream processes associated with materials production up to and including HMA and PCC mixing), materials transportation (transport of materials from the plant/quarry directly to the construction site), and construction equipment (equipment operated in the construction workzone). Although non-traditional, it is thought that this provides the most useful breakdown of emissions for someone associated with an individual project who is not a LCA expert.

Further Information
Details of input data can be found in *(25)*. Inventory calculations are done using the computational approach described by Heijung and Suh *(26)*. Matrices are viewable in the *Excel* version but not in the online version.

Impact Assessment
The impact model uses LCIA outputs of CO_2, NO_x, CO, SO_2, PM10, CH_4, N_2O, and volatile organic compounds (VOC) to produce impact metrics according to the Framework for Responsible Environmental Decision (FRED) and the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (*TRACI*) methods *(27,28)*. Specifically, *Roadprint* uses the following impact categories: GWP, acidification, eutrophication (all from FRED), and photochemical smog, and human toxicity (both from *TRACI*).

Online Delivery

Usability and broad access were the key factors considered for developing the online version of *Roadprint*. First, simple and intuitive interface design allows users to access *Roadprint* and its output in only a few minutes rather than what otherwise would take much longer in *Excel* or other format. Second, experience from Pavement Interactive *(29)* demonstrates that being freely accessible online can reach an audience 10-100 times what would otherwise be achievable. These factors directed the decision to build the tool as a web-based application versus an alternative option (i.e. client side download or *Excel*-based tool). Web-based also has maintenance advantages because software updates happen on the Web giving users immediate access to the new version, in contrast to downloading and installing client-side updates. The requirements for *Roadprint* online development included:

- Intuitive interface design
- Accessible via the web
- Fast performing, responsive application
- Stateful saving of generated reports
- Password secured access to generated reports
- Spreadsheet export capabilities

To meet these requirements a number of different common software development and web delivery platforms were evaluated. The criteria used to evaluate the platforms included broad device support (handhelds, tablets, laptops, and PC's), open source technologies, ease of administration and maintenance, strong security protocols, responsive performance, and scalability. The following software components were selected:

- Hosted operating system: *Linux*
- Web server: *Apache*
- Database: *MySQL*
- Server Side Scripting Language: *PHP*
- Web Markup Language: *HTML5*
- Client-side scripting language and UI elements: *JQuery*
- Data interchange layer: *JSON* (javascript object notation)

The end result of online development was a five-step interface shown in Figure 2.

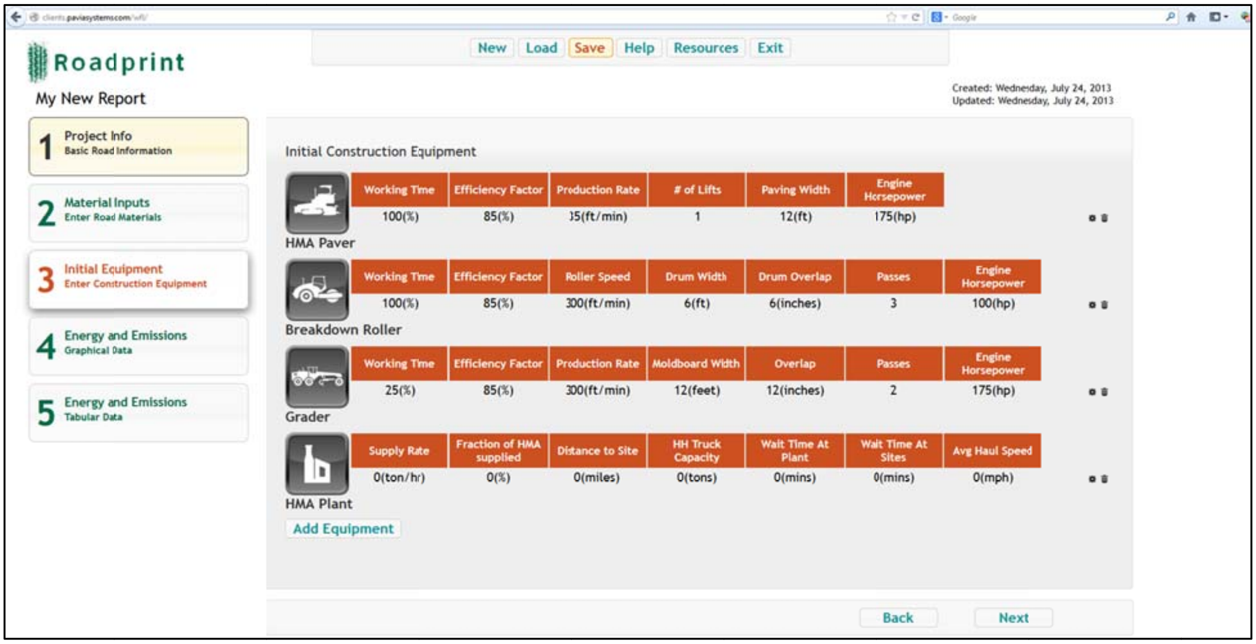

Figure 2: *Roadprint* online screenshot.

ROADPRINT ASSESSMENT USING WSDOT STANDARD PAVEMENTS

Models typically undergo a calibration or validation process to check their predictions against directly observable field measurements. However, currently there is no comparative data set or actual observations with a similar system boundary to *Roadprint*, and collecting such data was beyond the scope of this work. As a reasonable proxy for validation, this section describes one of several procedures used to test *Roadprint*. *Roadprint* was used to evaluate two WSDOT standard pavement designs for 25 to 50 million equivalent single axle loading (ESALs) as taken from *(30)*. The functional unit was a one lane-mile (one mile long and 12 feet wide) pavement able to service the given loading in accordance with WSDOT policy.

Inputs

Key input parameters were:

- Analysis period: 50 years
- HMA pavement
  - Initial design: 11 in. of HMA over 7 in. of crushed stone base
  - Maintenance: mill off and replace the top 1.8 in. 3 times
  - Mix design: 5% bitumen, 85% crushed rock, 10% sand, no RAP or WMA
  - Feedstock energy: 40.2 MJ/kg (*24*)
- PCC pavement
  - Initial design: 11 in. of jointed plain concrete pavement with 11 dowel bars per joint, over 4.2 in. of HMA, over 4.2 in. of crushed stone
  - Maintenance: none (diamond grinding was assumed but not modeled)
  - Mix design: 3,000 psi 28-day compressive strength ready mix concrete (*19*) with 20% fly ash
- Transport: truck transport of 31 miles (50 km) for all items
- Construction equipment

- HMA initial construction: grader, 2 excavators, backhoe, loader, 2 HMA pavers, material transfer vehicle, 2 breakdown rollers, finish roller, milling machine.
    - HMA maintenance: same as initial construction except no earthwork equipment.
    - PCC initial construction: grader, 2 excavators, backhoe, loader, 2 PCC spreaders, PCC paver, 2 HMA pavers, material transfer vehicle, 2 breakdown rollers, finish roller, milling machine.
    - PCC maintenance: none
- Mix plants: 200 ton/hr HMA plant, 325 ton/hr (162.5 yd^3/hr) PCC plant

Detailed input descriptions are contained in *(25)*.

Impact Assessment

Table 2 summarizes *Roadprint* results.

Table 2: Impact Assessment Results for 1 Lane-Mile of 25-50 Million ESAL Standard WSDOT Pavements (Feedstock Energy[a] is Excluded)

Impact	Energy Consumption		Global Warming Potential		Acidification		Photochemical Smog		Eutrophication		Human Health Criteria Air	
Unit	Energy (GJ)[b]		GWP (CO_2Mg-E)[b]		Kg SO_2[b]		Kg NO_X[b]		Kg PO_4[b]		milli-DALYs	
HMA pavement (11 in. HMA over 7 in. crushed stone base)												
Material Production	5,535	74%	251	62%	825	19%	799	49%	77	44%	28	34%
Construction	544	7%	44	11%	235	5%	352	21%	41	23%	7	8%
Transportation	1,400	19%	107	27%	3,399	76%	493	30%	59	34%	47	58%
Total	7,478		402		4,460		1,644		177		81	
PCC pavement (11 in. JPCP over 4.2 in. of HMA over 4.2 in. of crushed stone)												
Material Production	4,598	80%	490	84%	1,544	42%	1,272	70%	155	71%	113	79%
Construction	379	7%	31	5%	168	5%	257	14%	29	13%	4	3%
Transportation	800	14%	61	11%	1,931	53%	281	16%	34	16%	26	18%
Total	5,777		582		3,644		1,810		218		144	

a. Feedstock energy is 13,840 GJ for HMA and 3,544 GJ for PCC.
b. The amount is reported in the first column, the fraction of the total (in percent) is reported in the second column.

In both pavements materials production dominates energy consumption and GWP (74% for HMA and 80% for PCC) while construction contributes about 7%. Transportation contributions are dependent on the mode and distance of transport for each item, but tend to account for 2-3 times the construction share for energy consumption and GWP and a higher fraction of the total for other impact categories. These findings are consistent with other research (see *(25)* for a summary of this research) and suggest that materials production should be the primary focus if the goal is to reduce environmental impacts.

Probabilistic Results

For these scenarios *Roadprint* also estimated probabilistic results for materials production, construction equipment operation, transportation, and construction productivity (Table 3). The probabilistic results reinforce the dominance of materials production. In the case of *Roadprint*, the large materials production variability comes from the wide range of estimated energy consumption and CO_2 emission values used by different tools and databases that was used to generate a portion of the uncertainty.

Table 3: Probabilistic Impact Assessment Results for 25-50 Million ESAL Standard WSDOT Pavements (Feedstock Energy is Excluded)

	Material Production		Transportation		Equipment Operation	
	Energy (MJ)	GHG (Mg)	Energy (MJ)	GHG (Mg)	Energy (MJ)	GHG (Mg)
HMA						
Mean	5535	251	1400	107	544	44
Std. Deviation	3881	37	23	2	11	1
90% conf. interval	829-11939	189-313	1362-1438	104-110	526-561	43-46
PCC						
Mean	4,598	490	800	61	379	31
Std. Deviation	1,217	113	12	0.9	4.7	0.4
90% conf. interval	2,596-6,601	305-677	781-819	60-63	371-387	30-31

DISCUSSION

Issues with Pavement LCA

Issues with pavement LCA discussed previously almost ensure that results from quantification tools such as *Roadprint* cannot be repeated unless the exact same information and tool is used. These issues are not likely to be resolved by the scientific community any time soon if ever. Therefore, if pavement LCA is to become broadly accepted the pavement community would benefit from a standard set of LCA rules and data sources analogous to the standards put forth by the FHWA *(14)* for life cycle cost analysis (LCCA). Such a method is underway with the FHWA's Sustainable Pavement Technical Working Group. If such a method specifies particular databases and system boundaries then there is potential to compare pavement LCAs across conforming tools. If it only specifies transparency in reporting these items then comparisons will not be valid, although they will likely continue to be done.

State of the Practice

There are no current U.S. requirements for pavement LCA use. Use will likely be driven by accounting policies driven by national, state-level, and local GHG reduction mandates (e.g., California AB 32) or cap-and-trade schemes, or rating system requirements. It may be that alternative bidding could include LCA results for proposed projects; however, experience with including LCCA in such processes tends to results in inconsistent methods, or strenuous argument over methods and assumptions used. Therefore, as a minimum, pavement LCA tools ought to be able to inventory GHG from pavement construction (e.g., materials production, transportation, and construction activities) relatively quickly using existing construction data (e.g., bid tabulations), and general data available early in the project planning stage. Modeling use phase results may be helpful in decision support, but may not be for simple accounting procedures. The predictive nature of use phase modeling along with its large uncertainty and long time horizon may not be consistent with GHG and other environmental accounting practices.

Roadprint Assessment

Roadprint is able to perform a pavement LCA and differentiate between standard WSDOT pavement designs. Results agree with previous findings *(31)* that materials production tends to dominate results with construction activities being somewhat insignificant.

- **Used by pavement practitioners**. *Roadprint* is used in several college courses and has been, at this point, anecdotally reported as reasonably user friendly. Usability input from two classes (about 40 students all together) was used to refine the *Roadprint* interface once.
- **Freely accessible on the Web**. *Roadprint* is freely accessible at: http://www.pavementinteractive.org/Roadprint
- **Use currently available general data**. *Roadprint* data is all currently available and free. It contains no proprietary data, paid-for data, or data generated as a result of this project. Issues with the use of this generally available data were discussed previously.
- **Readily updated when new data are available**. The capability for updates exists, but will cost money and have not been tested.
- **Transparent about its data sources and quality**. This paper and Lin *(25)* currently supply this transparency but a user's manual is being developed to make the information more readily available to the user.
- **Able to differentiate between key paving practices**. The test on WSDOT pavement sections serves an example of this ability. Other tests, not reported here are consistent with the WSDOT results.

Other key findings are:

- A rudimentary probabilistic assessment indicates that there is much uncertainty in results with materials production uncertainty dominating. This uncertainty must be addressed in attempts to mainstream pavement LCA. Otherwise, the false precision supplied by a singular deterministic answer may unfairly influence decisions.
- Modeling construction productivity (as *Roadprint* does) is not advisable considering its relatively small contribution to the results. A simpler approach would be to require the user to select key construction equipment and then have the program use a default productivity (as other tools do).

CONCLUSIONS AND RECOMMENDATIONS

This paper describes the development of *Roadprint*, an online pavement LCA tool designed to be used by pavement practitioners, be freely available on the web, and provide useful results given currently available data and known pavement LCA issues. This description brings to light key issues associated with pavement LCA. Specific conclusions and recommendations are:

- ***Roadprint* is able to perform pavement LCA**. Despite poor quality data and limitations in scope (e.g., no use phase, simplification of WMA and recycled materials) *Roadprint* is able to provide useful outputs that can differentiate between different pavement materials, transport distances, and construction equipment.
- **Standard LCA issues limit the wide-scale use of pavement LCA**. Inconsistencies in scope, poor data quality, differing and interpretable impacts, and other issues have resulted in an inability to compare results across pavement LCA tools, or to create any standards or benchmarks.
- **Pavement LCA will remain a research-level topic in the absence of Federal or State mandates**. There appears to be much research interest but little call for practical use outside of researchers. A single, forceful mandate may change this outlook completely.
- **A useable pavement LCA tool will involve numerous simplifications, which will push the boundaries of standard LCA methods**. It is not likely that LCA will be implemented on a large scale by specialists; rather it needs to be accessible to transportation/pavement engineers. In order to do so simplification is needed that does not invalidate the LCA process. Beyond this, there will

always be an important role for LCA specialists both for detailed analysis, and for maintaining/scrutinizing the standards set for general use.

- **Most LCA impact categories are flawed or not understood**. While it is possible to report numerous impact categories, those beyond GWP and energy consumption carry very little meaning to the practitioner and suffer from a number of flaws *(see 10,11)*.
- **Online delivery is mandatory to achieve broad reach**. Experiences with Pavement Interactive show that online reach can be several orders of magnitude more than paper, installable software, or even downloadable files.

The following recommendations are made:

- **Develop a standard pavement LCA method.** Otherwise pavement LCA will remain a boutique tool. Current pavement LCA issues require high-level guidance to overcome. A standard method, similar to that put forth by the FHWA for LCCA *(14)* is needed. This effort is underway now with the FHWA's Sustainable Pavement Technical Working Group.
- **Expand the LCA scope to include the entire road project**. Limiting LCA to just the pavement section excludes potentially impactful roadway contributions from such things as structures, earthwork, and lighting *(e.g., 1,31)*. Typically, the public and decision-makers view the road as a whole and do not often view the pavement as a separate stand-alone system.
- **Clearly communicate key boundary and modeling parameters**. As a minimum, the following should be communicated: system boundary, data sources and quality, allocation involving recycled materials, construction equipment and WMA modeling method, inclusion/exclusion of feedstock energy and its value. A more thorough reporting akin to that developed at *(32)* is desirable.
- **Expand the number of unit processes in *Roadprint***. Potentially impactful unit processes currently excluded by *Roadprint* include use phase processes such as workzone traffic delay, daily traffic, and even carbonation.
- **Gather and make available better data**. Data for many processes are old and sparse and do not meet (*24*) criteria for "high-quality" data. Specifically, U.S. bitumen, warm mix asphalt, and recycled materials data are lacking. This will likely be an industry initiative if anything. However, it is not likely to happen until a standard pavement LCA method is agreed upon.
- **Use LCA for inventory and process improvement only**. Comparison using different tools or between significantly different pavement types (e.g., PCC and HMA) is not warranted.

ACKNOWELDGEMENTS

This research was sponsored by the Coordinated Federal Lands Highway Technology Implementation Program (CTIP), the Washington State Department of Transportation (WSDOT), and the Oregon Department of Transportation (ODOT).

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